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PHYSICAL CHARACTERISTICS AND DOSES OF SPACE RADIATIONS

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ABSTRACT

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A survey of data on galactic cosmic radiation, Van Allen belt radiations, and solar cosmic radiation is presented. On the basis of these data, that still contain large uncertainties in some cases, upper and lower limits of rad doses which would have been encountered in the past solar cycle under practical amounts of mass shielding are estimated.

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PHYSICAL CHARACTERISTICS AND DOSES OF SPACE RADIATIONS

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INTRODUCTION

At present three kinds of energetic space radiations which may constitute a potential radiation hazard in space flight are known:

(1) The so-called galactic cosmic radiation

(2) Van Allen belt radiations

(3) Solar cosmic radiation

Galactic cosmic rays consist of about 85 percent protons, 13 percent α-particles, and 2 percent heavier nuclei, stripped of all electrons, of extremely high energy (average energy of protons $\approx$ 4 Bev). In free space these primaries arrive from all directions of the sky with equal intensity. From the viewpoint of implications to space flight, the most important fact is that their flux is low, namely, 2.5 particles/cm^2-sec, during solar activity years - about 10,000 times lower than the flux within the inner Van Allen belt or during extreme flare proton events; consequently, the overall ionization rate per gram or per cm^3, that is, the physical dose rate, is also low. By carefully taking into account the high specific ionization of heavier primaries and their higher RBE[1] a biological dose rate of 0.45 rem/week (ref. 1(a)) is calculated in free space for solar activity years, secondaries which originate in the spaceship and in the human body itself being neglected.

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[1]Relative Biological Effectiveness. (See, for example, ref. 11.)

During solar minimum years the dose rate would be higher by a factor of about 2. This rate is, of course, orders of magnitude more than the radiation dose which man receives on sea level under 1,000 g/cm^2 atmosphere and under protection of the magnetic field of the earth. However, this dose rate does not surpass substantially the maximum permissible dose rate which is stated for atomic workers according to the recommendations of the International Commission for Radiation Protection (ICRP), i.e., 0.1 rem/week when continuously received over 50 years of professional duty. Shielding against the overall ionization produced by galactic cosmic rays appears to be impractical for the present generation of space vehicles since up to 80 g/cm^2 wall thickness increases the ionization dose at least during solar activity years when low-energy primaries are diminished. The biological effectiveness or biological dose would be, of course, lower with heavy shielding than without since the flux of the more heavily ionizing primaries and secondaries is reduced.

Special attention on the part of scientists and biologists is directed to one component of galactic cosmic rays, the heavy primaries. (See, e.g., refs. 1(b) and 2.) The heavy ionized end of such a heavy primary track ("thin-down") is longer by orders of magnitude and the ionization is spread over a 10 to 20 fold higher cross section than that of an α-particle track (length $\approx 30\mu$, cross section $\approx 0.5\mu$). The effect of heavy primary hits on sensitive organs such as the receptor cells of the eye which the body cannot replace is expected to be more important than would be anticipated from their small contribution to the total ionization. The number of hits/cm^3 and day is, however, very low as seen in figure 1 which shows the number of hits as function of altitude extrapolated by Yagoda (ref. 3) from balloon measurements.

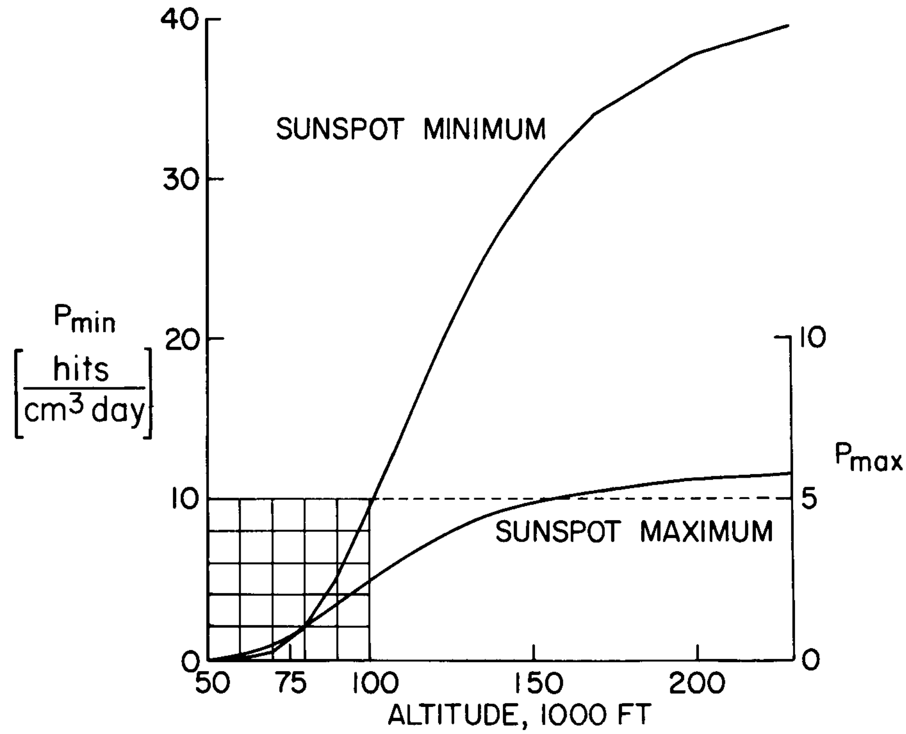

Figure 1.- Variation of thin-down intensities with altitude for seasons of maximum and minimum sunspot activity. (Reproduced from ref. 3, H. Yagoda.)

Shielding against this radiation would be an easier task. A residual air layer of 36 g/cm^2 (75,000-foot altitude) would reduce the number of hits by a factor of 40 during solar minimum years and by a factor of 6 during activity years.

VAN ALLEN BELT RADIATIONS

The radiation trapped within the Van Allen belts consists mainly of protons and electrons of high intensities with energies up to 700 Mev and some Mev, respectively.

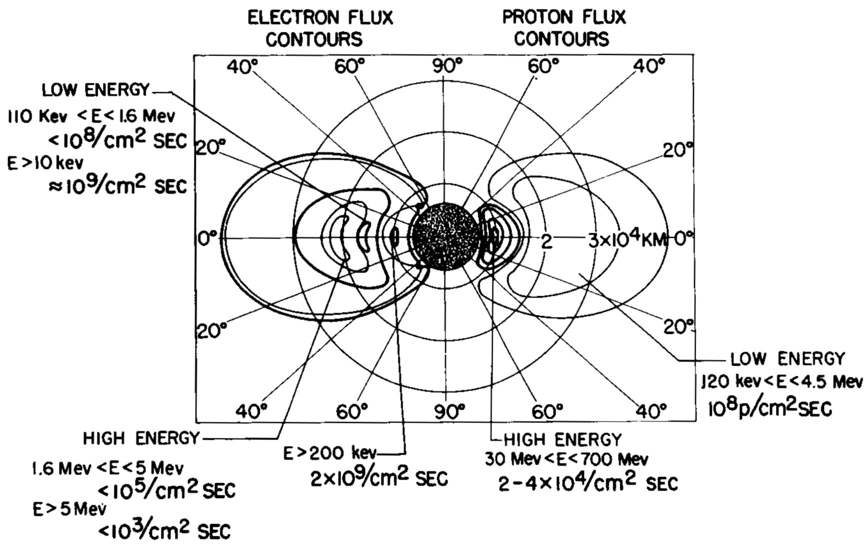

Figure 2.- Energetic particle fluxes in the Van Allen Belts (as of Fall 1961) schematic survey.

Figure 2 represents a schematic survey of their fluxes and energies according to more detailed measurements with Explorer XII (Fall 1961, see refs. 4 to 8).

The most important belt component from the viewpoint of implications to space flight are the energetic protons of 30 to 700 Mev energy, which are mainly encountered in the inner belt with maximum intensity of 20 to 40×10^4 protons/cm^2-sec in about 3,000-km altitude. Based on Freden White's spectrum, the following proton doses in the belt center as functions of shielding are obtained (see fig. 3)[2]:

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[2]The figure is based on $N = 20{,}000$ p/cm^2-sec, $E > 40$ Mev in the center of the belt. The difference between rep and tissue rad is 7 percent and is considered as insignificant in the light of present uncertainties.

For 2 g/cm^2 outer shield 24 rad/hour

25 g/cm^2 outer shield 6 rad/hour

if 40,000 $protons/cm^2$-sec, $E > 40$ Mev in the center of the belt is assumed.

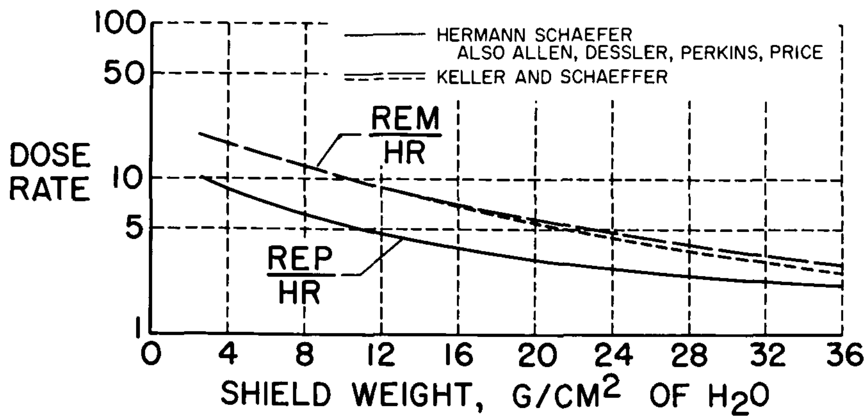

Figure 3.- Dose rates in center of spherical shields neglecting self-shielding of the body. (See: Schaefer, Hermann J.: Tissue Depth Doses in the High Intensity Proton Radiation Field of the Inner Van Allen Belt. Rep. No. 16, U.S. Naval School of Aviation Medicine (Pensacola, Fla.), Nov. 10, 1959. Keller, J. W.: A Study of Shielding Requirements for Manned Space Missions. FZK-124 (Contract No. NASw-50), Convair, Oct. 10, 1960. Allen, R. I., Dessler, A. J., Perkins, J. F., and Price, H. C.: Shielding Problems in Manned Space Vehicles. NR-104 (Contract No. DA-01-009-506-ORD-832), Lockheed Nuclear Products (Marietta, Ga.), July 1960.) The rem dose rates are calculated by J. W. Keller assuming for protons and neutrons of $E > 40$ Mev RBE = 1 and of $E < 40$ Mev RBE = 2. The long-dashed line indicates the rem dose including the contribution of secondary neutrons.

These are upper limits of dose rates since self-shielding of the human body is neglected and the spectra fall off steeper on different locations of the belt.

The natural electrons appear to be not very important from the viewpoint of radiation doses inside a vehicle with a few g/cm^2 wall thickness in which the electrons themselves are absorbed and produce x-radiation. The x-radiation dose rate amounts to substantially less than 2 rem/hr (2 rad/hr behind 30 mil steel, based on conservative upper limits of spectral fluxes, see ref. 9).

In summary it may be said that the belt radiations do not constitute an acute danger if the belts are passed in about 2 hours, a time which is characteristic for Pioneer III, IV, and V or escape missions. If the stay in the center of the inner belt lasts for 2 days, however, even with 25 g/cm^2 shielding, the proton dose would be >200 rad. This value is on the critical limit for acute radiation sickness.

SOLAR COSMIC RADIATION

Solar cosmic rays are identified as transient energetic particle showers, mainly protons, associated with flares in the solar chromosphere. In some cases the particle streams encountering the earth have an intensity of protons of lower energy ($E > 30$ Mev) four to five orders of magnitude higher than that of galactic cosmic protons and have a duration of the maximum phase in the order of 1 day. Residual low intensities are observed up to 10 days after one flare (July 16, 1959). The intensities and durations of proton fluxes vary in a large degree for different events. About 5 to 13 low- and medium-energy events or event groups with proton energies up to 500 Mev or 2 Bev, respectively, occurred during past solar activity years from 1957 to 1959, that were intense enough to be detectable with instrumented high-altitude balloons and riometers.[3]

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[3]A radio ionospheric opacity meter is used to measure absorption of galactic radio noise in the ionosphere. A strong D-layer in the lower ionosphere is preferably produced by flare protons.

The frequency of such extreme events which could constitute a significant radiation hazard in a lightly shielded vehicle was, of course, only 2 to 4 during the most active years of the last solar cycle. Even less frequent are high-energy events of high intensity and duration, with particle energies up to $E > 10$ Bev. Such events were observed by means of their secondary mesons and neutrons monitored at ground level during the two last solar cycles. Only one or two such high-energy events occurred about every 4 years at the increasing or decreasing phases of the sunspot cycles.

The time profiles of intensities of particles in the Bev range for two events are shown in figures 4(a) and 4(b).

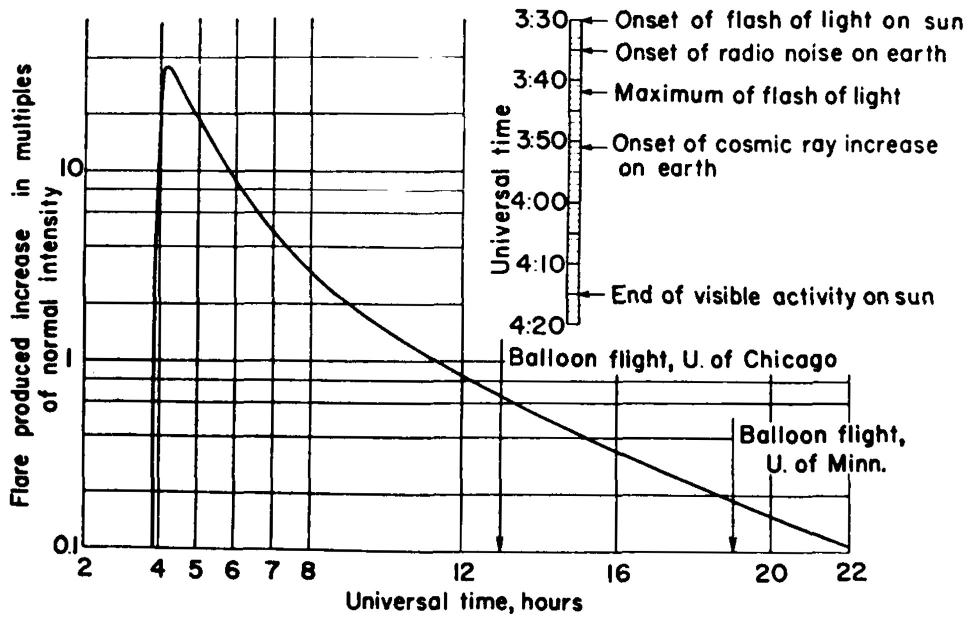

Figure 4(a).- Cosmic-ray neutron surge at sea level during large solar flare of February 23, 1956. Observed by Lockwood et al. at Durham, New Hampshire. (Reproduced from ref. 1(b).)

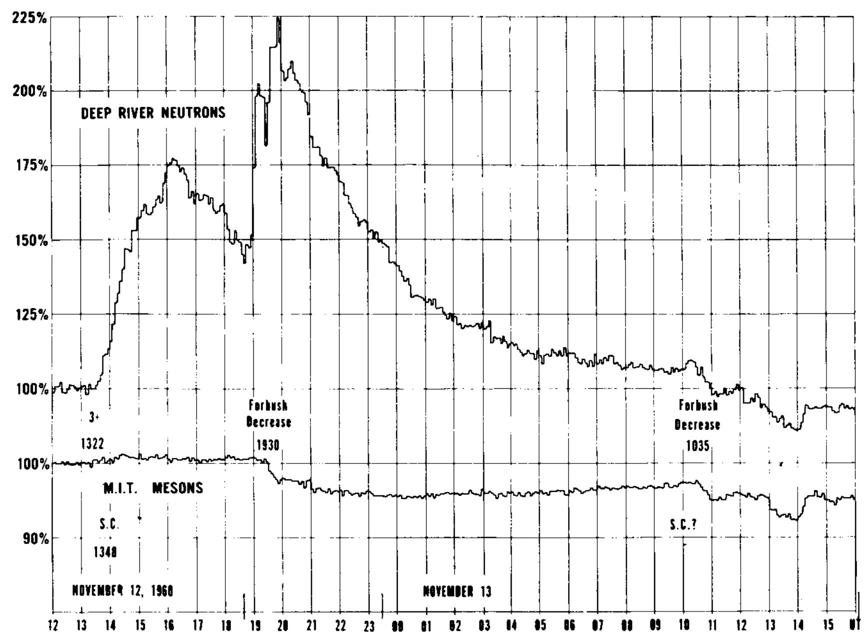

Figure 4(b).- Neutron surge at sea level in Deep River, Canada from November 12 to November 15, 1960 and meson decrease measured at Massachusetts Institute of Technology. (J. F. Steljes, H. Carmichael, and K. G. McCracken, ref. 10.)

In the case of the February 23, 1956 event the neutron intensity at sea level rises to 3,600 percent of normal. The intensities of the lower energy particles decay more slowly as seen in high-altitude balloon and riometer records.

Some proton energy spectra measured during extreme events are shown in figure 5. During the February 23, 1956, high-energy event, the most intense observed during the last two solar cycles, two spectra are derived from measurements at +1 hour (prompt) and +19 hours after the flare. For the November 12, 1960 medium-energy event of extreme flux and duration, the spectra at +5 and +32 hours after the flare are given. For the May 10, 1959 high-flux low-energy event only the spectrum at +32 hours is measured. The absolute intensity in the energy range $E > 100$ Mev given for the time +32 hours after the flare seem uncertain by a factor of about 4. In this figure the more recent lower values are inserted.[4]

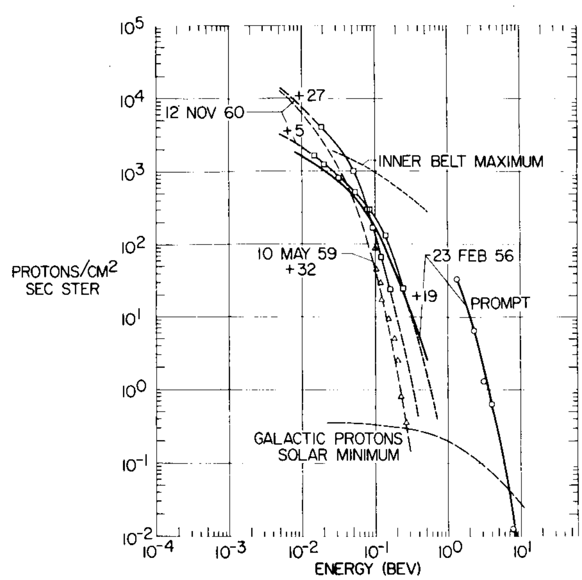

Figure 5.- Integral energy spectra of solar cosmic rays, inner belt protons and galactic protons (Basic data and references, see in ref. 11).

[4]The references from which these spectra are determined are given in reference 11 together with the methods used for dose rate and dose calculations. For the May 1959 event in reference 11, according to preliminary data and extrapolations, higher flux values and an E^{-4} spectrum are used. The latter was extrapolated to bend over only for very low energies and gives substantially higher dose rate values especially behind low shielding. Also in the case of July 14 the doses in reference 11 inferred from preliminary extrapolations of the spectrum at +30 hours and of very high intensities close to the time of the flare are substantially too large. More recent analyses of data on intensities and time profiles indicate substantially lower time-integrated fluxes for these low-energy events.

Most of the spectra fall off very steeply in the energy range $E > 80$ to 100 Mev and steeper than the belt protons or galactic protons. This property suggests the conclusion that the main intensity can be cut off by shielding in the order of 10 to 25 g/cm^2 (range of protons of 100 to 200 Mev). From the spectra the dose rates behind different shields can be obtained by a routine calculation - if secondaries are neglected - for that particular instant for which the spectrum is valid. (See, for example, ref. 11.) To obtain doses accumulated during the whole event, these dose rates have to be multiplied by the times for which the respective spectra are considered as constant and these products have to be summarized or integrated. Since the time variations of intensities or spectra are not well known in some especially important cases, only approximate upper and lower limits of doses are given in figure 6 for the largest events known.

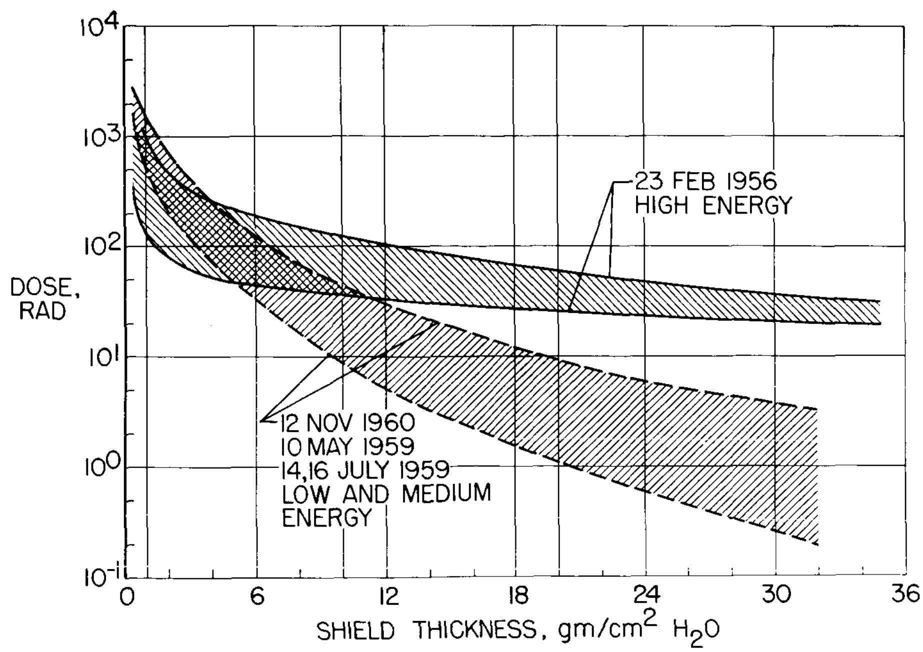

Figure 6.- Flare proton doses in the center of spherical shields when self-shielding is neglected.

The broad strip for medium- and low-energy events corresponds in its upper limit to the doses of the November 12, 1960, July 14, 1959 and July 16, 1959 events; in its lower limit, to the May 10, 1959 doses, the latter which might have been higher. From the steep fall off of doses with shielding thickness, it follows that the doses also fall off very fast in men's bodies. The high-energy event of February 23, 1956, is, of course, more penetrant. Its time-integrated fluxes in the low energy range were, however, apparently lower than those of low-energy events and the fluxes in the high energy range yield depth doses which would not have reached the critical limits of 100 to 200 rad.

The doses given in figure 6 are upper and lower limits of rad as measured in a small ionization chamber in the center of spherical shields of different thicknesses (abscissa), self-shielding of man's body inside the shield being neglected. If the shield consists of water, the g/cm^2 value on the abscissa gives the thickness of the shield in centimeters. For a more realistic appraisal of the surface and depth dose within the human body, it has to be taken into account that organs on the surface as in the depth of the body are protected from one or all sides by the body itself. Thus an inner organ receives a dose which can be read from figure 6 by adding to the outer shield thickness the average thickness of the surrounding tissue which might be in the order of 10 to 15 g/cm^2. Also the doses on the body surface are substantially lower than those read from figure 6, when only the outer shield is taken into account. A fair approximation of doses received on organs on the surface (skin, eyes, and gonads) is obtained by dividing the reading by the factor 2 and thus neglecting the radiation from one side or from a solid angle 2π.

If self-shielding is taken into account, the doses in the depth of the body also under low outer shielding remain below 25 rad in most cases except in the high-energy event of February 23, 1956 ($\approx$50 rad). On the other hand, under 1 g/cm^2 outer shield, an occupant, if self-shielding is taken into account, would receive a dose of up to 1,000 rad on the surface of his body during extreme low- and medium-energy events. This dose is above the acute permissible limit for eyes and gonads and even above the skin erythema dose. In dimensioning the shielding, it has to be taken into account that the probability of occurrence of multiple events such as those after the flares on July 10, 14, and 16, 1959, for example, even for a 14-day expedition, is not a negligible quantity; furthermore, the tissue rad dose has to be multiplied by about an RBE factor of 1.5 for solar protons to obtain the X-ray equivalent dose in rem and that the above estimates are considered as uncertain within a factor of about 2.

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